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Disinfection of Contaminated Water by Using Solar Irradiation

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Contaminated water causes an estimated 6 to 60 billion cases of gastrointestinal illness annually. The majority of these cases occur in rural areas of developing nations where the water supply remains polluted and adequate sanitation is unavailable. A portable, low-cost, and low-maintenance solar unit to disinfect unpotable water has been designed and tested. The solar disinfection unit was tested with both river water and partially processed water from two wastewater treatment plants. In less than 30 min in midday sunlight, the unit eradicated more than 4 $\log_{10}$ U (99.99%) of bacteria contained in highly contaminated water samples. The solar disinfection unit has been field tested by Centro Panamericano de Ingenieria Sanitaria y Ciencias del Ambiente in Lima, Peru. At moderate light intensity, the solar disinfection unit was capable of reducing the bacterial load in a controlled contaminated water sample by 4 $\log_{10}$ U and disinfected approximately 1 liter of water in 30 min.

Contaminated water causes an estimated 6 to 60 billion cases of gastrointestinal illness annually. The majority of these cases occur in rural areas of developing nations where the water supply is polluted with a variety of microorganisms, including viruses, fecal coliforms, and protozoa, and adequate sanitation is unavailable. The need for a low-cost, low-maintenance, and effective disinfection system for the improvement of water quality is high.

Conventional technologies used for disinfection of unpotable water include ozonation, chlorination, and artificial UV radiation. These technologies are capital intensive, require sophisticated equipment, and demand skilled operators (1, 16, 22). At the household level, boiling water for about 10 min or the use of certain chlorine compounds available in tablets (halazone or calcium hypochlorite) or solutions (sodium hypochlorite at 1 to 2 drops per liter) is commonly used to disinfect drinking water. A lack of resources and/or distribution infrastructure makes the application of these procedures extremely limited in developing countries where waterborne diseases are prevalent. Even if these methods are available and affordable, their implementation could be environmentally unsound or hygienically unsafe when performed by a layperson. Boiling, for example, requires about 1 kg of wood/liter of water, and misuse of sodium hypochlorite solution poses a safety hazard (2, 3, 10).

The use of solar irradiation for treatment of chemically and biologically contaminated water is not a new phenomenon (4, 7, 8, 15, 18–20). Solar radiation removes a wide range of organic chemicals and pathogenic organisms by direct exposure, is relatively inexpensive, and avoids generation of harmful byproducts of chemically driven technologies (4). More importantly, the economics of the process are almost volume independent (9).

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The bacterial inactivation rate in a contaminated water sample is proportional to the intensity of sunlight and atmospheric temperature and inversely proportional to the water depth (2). While sunlight can penetrate into water, its intensity decreases with the depth of penetration due to scattering caused by suspended particles present in the water (2, 6a). The reduction in intensity varies with wavelength; for wavelengths ranging from 200 to 400 nm the reduction in intensity does not exceed 5%/m of water depth; however, it rises as high as 40%/m for longer wavelengths (2).

The synergistic effects of two irradiation wavelengths (23, 24) and of light and heat (21) and the action of light on bacteria and living cells have been well documented (11–13). The most effective wavelengths for microbial destruction are the near-UV-A band (320 to 400 nm) and to a lesser extent the visible band of violet and blue light, 400 to 490 nm (2, 21). While there was no appreciable difference in the rate of bacterial inactivation for sample temperatures ranging from 12 to 40°C, when the water temperature was increased to 50°C, the same fraction of the initial population of *Escherichia coli* was inactivated by a much lower fluence (a threefold reduction [24]). This reduction was presumably due to the synergetic effects of solar radiation and thermal water treatment (24). While pasteurization of water occurs at 72°C (161°F) in a minimum of 15 s (5), bacterium-free water can be obtained by solar irradiation at lower temperatures with much longer residence times (5, 14).

Many researchers have reported results from limited laboratory studies under narrowly defined radiation bands (21, 23, 24). The polychromatic nature of solar light and its varying intensity with geographic location of incidence complicate extrapolation of these results and their implementation in actual designs. Additionally, different microorganisms behave differently when subjected to multiple irradiation wavelengths (2, 8, 19, 20, 24). Based on preliminary batch work, a solar disinfection unit was designed and constructed. In this study, the unit was used to measure bacterial inactivation of highly contaminated water from two wastewater treatment plants. The unit

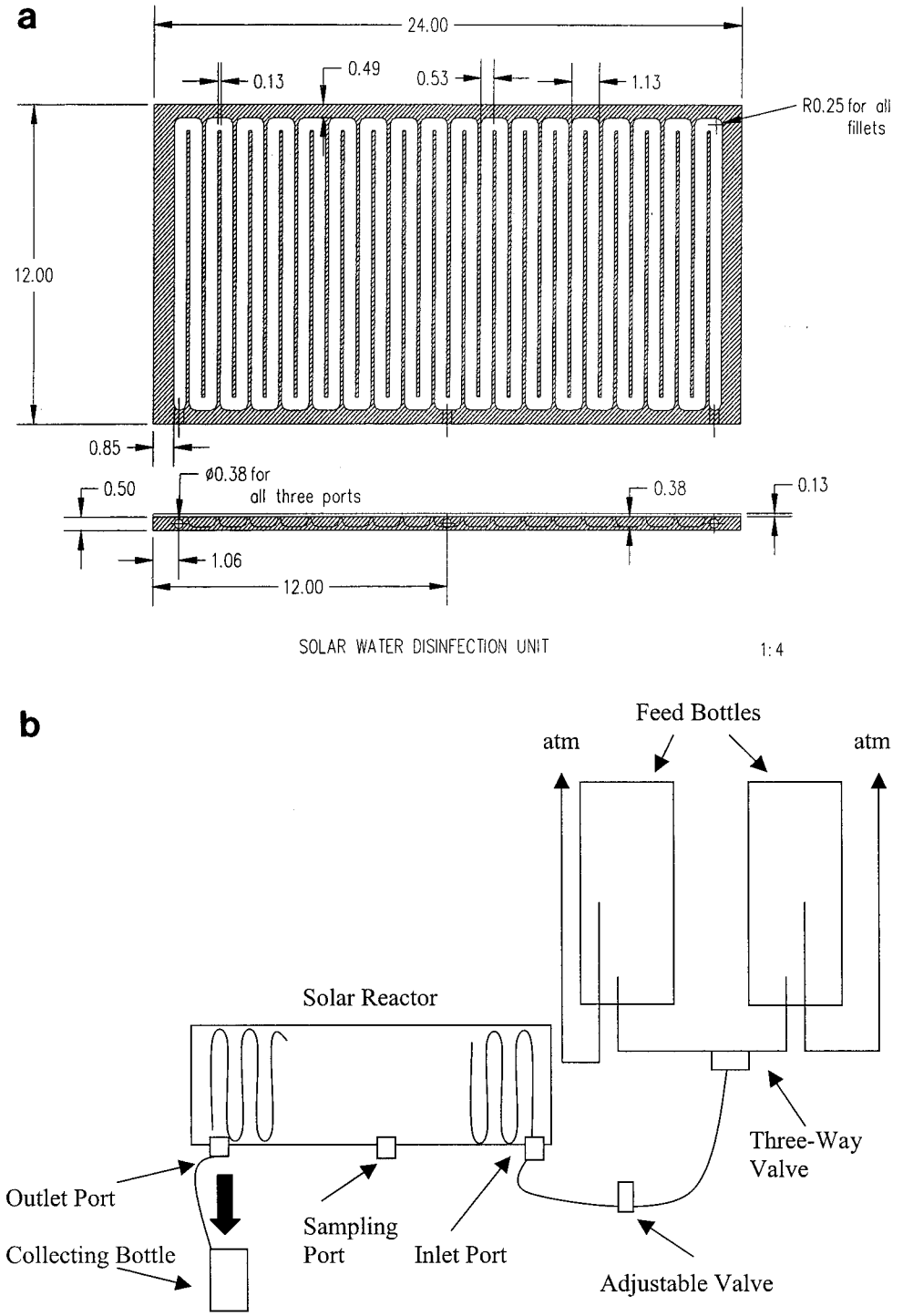

FIG. 1. (a) Solar disinfection unit base. Dimensions are in inches. (b) Solar water disinfection apparatus. The reactor is made of a 12- by 24- by 1/2-in. dark gray PVC base with a UV transmitting cover. The feed and collecting bottles are 2-liter transparent plastic bottles covered with white contact paper.

also was evaluated by the Centro Panamericano de Ingenieria Sanitaria y Ciencias del Ambiente (CEPIS) in Lima, Peru. The experimental results obtained by CEPIS using the solar disinfection unit with controlled contaminated water samples are reported.

MATERIALS AND METHODS

Solar disinfection unit. The solar disinfection unit is composed of two parts: a base (Fig. 1a) and a cover. The base was a 12- by 24- by 1/2-in. dark gray polyvinyl chloride (PVC) plate machined with snake-shaped grooves (1/2 in. in diameter and 3/8 in. in depth) running across the plate from one end to the other. A 12-

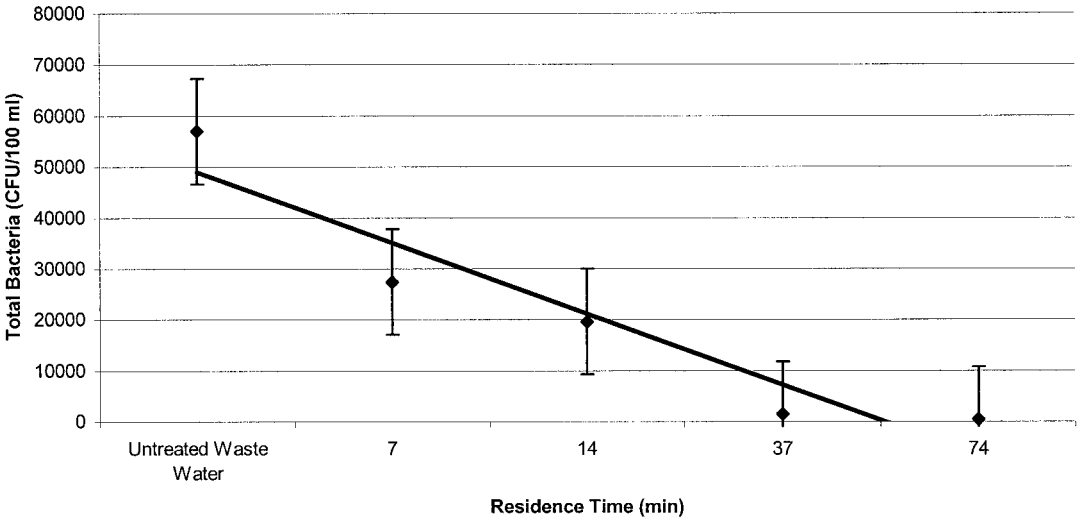

FIG. 2. Change in total coliform counts with increasing residence times in the continuous solar disinfection unit for municipal wastewater samples. Each data point represents the average of three samples. Error bars indicate standard errors.

by 24- by 1/8-in. UV transparent acrylic plate covered the base permanently to keep the heat inside and prevent any air from entering the system when the unit was in operation. The acrylic cover was glued to the PVC base with "Weld-On 40" acrylic cement (IPS Co., Gardena, Calif.). The volume of the disinfection unit was approximately 1 liter.

In operation, the solar disinfection unit consisted of the unit and three 2-liter transparent bottles: two were used as feed bottles, and one was used as a collection bottle (Fig. 1b). Three 1/4-in. openings tapped with self-locking valves along one side of the plate served as inlet, sampling, and outlet ports, respectively. The bottles were covered with nontransparent white contact paper to eliminate any pre- or postreactor sunlight interference. The feed bottles were capped with a rubber stopper having two 1/8-in.-diameter holes. Two copper tubes were run through these holes, one approximately 2 in. longer than the other. The longer stem was open to the atmosphere via flexible tubing on the outer end. The shorter stem was connected to the inlet port of the solar unit (Fig. 1b). The 2-in. head provided uniform flow rate, controlled with an adjustable valve, throughout a run.

Sample collection. Water was taken from three different sources: two local municipal wastewater treatment plants in Phillipsburg, N.J., and Easton, Pa., and the Delaware River in Easton, Pa. Water from the treatment plants was sampled between the postsecondary clarifier and chlorination processes. Water used in all experiments, except turbidity studies, was relatively clear and free of visible suspended solids. Water used in turbidity studies was transparent, with nephelometric turbidity unit (NTU) values between 0.09 and 0.32.

Sample treatment. The disinfection unit was tilted upward at the outlet end for approximately 1 in. to aid escape of any trapped air. Once the disinfection unit was filled with water, it was allowed to run for more than 1 unit volume at the set flow rate before any samples were collected. Multiple 100-ml samples (usually three) were collected at 10-min intervals for each of the residence times, which ranged from 5 to 74 min. Trials were conducted in June, July, and August 2000, under clear skies at ambient temperatures ranging from 22.9 to 33.3°C in Easton, Pa., between 11 a.m. and 3 p.m. to ensure the highest sunlight intensity.

Sample testing. The pH, dissolved oxygen (model 50 B; YSI Inc., Yellow Springs, Ohio), turbidity (HF Instruments DRT 100B; Shaban Manufacturing, Inc., Fort Myers, Fla.), nitrate (method 8507; Hach Co., Loveland, Colo.), orthophosphate (method 8048; Hach Co.), and temperature of water flowing in and out of the solar disinfection unit were monitored for all runs. Samples collected from the solar disinfection unit were filtered through a 0.45-μm-pore-size sterile membrane filter (Millipore Co., Bedford, Mass.). The filters were then placed into a 47-mm-diameter sterile Millipore petri dish (Precision Scientific Group, GCA Co., Chicago, Ill.) with m-ColiBlue24 broth-saturated pads (Millipore Co.; method 10029 [Hach Co.]) and incubated at 35°C for 24 h. A sample of the wastewater or river water was tested on the morning of each trial. Total coliforms and *E. coli* bacteria were counted following incubation.

Water samples from the solar disinfection unit were tested by Benchmark Analytics Laboratory (Center Valley, Pa.) using standard method 9222B, which corresponds to EPA-600-R-00-013 for *E. coli* (6). The limit of detection is <1 coliform/100 ml of water (6).

The unit also was field tested by CEPIS in Lima, Peru. Sunlight intensity was measured using a Haeni Solar 130 solarimeter. Tap water samples were inoculated with an overnight culture of mixed coliforms (*Escherichia*, *Klebsiella*, *Enterobacter*, and *Citrobacter* spp.) at 10^5 CFU/100 ml. Water samples were run through the solar disinfection unit, and effluent was tested by membrane filtration with sulfate lauryl broth (17) followed by incubation at 44 ± 0.1°C for 24 h. Total coliforms on the filters were counted.

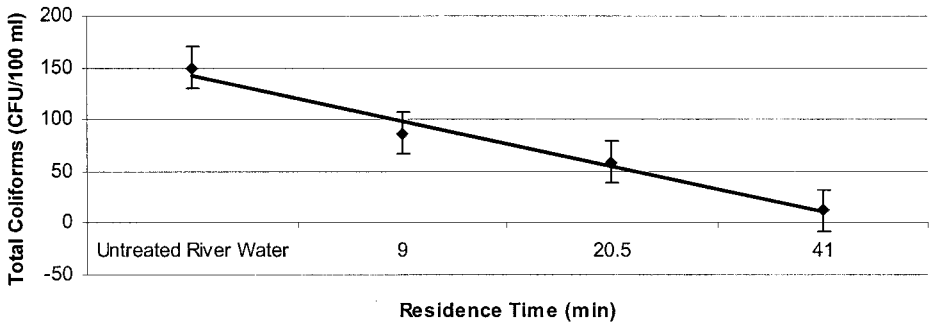

FIG. 3. Change in total coliform counts with increasing residence times in the continuous solar disinfection unit for Delaware River water. Each data point represents the average of three samples. Error bars indicate standard errors.

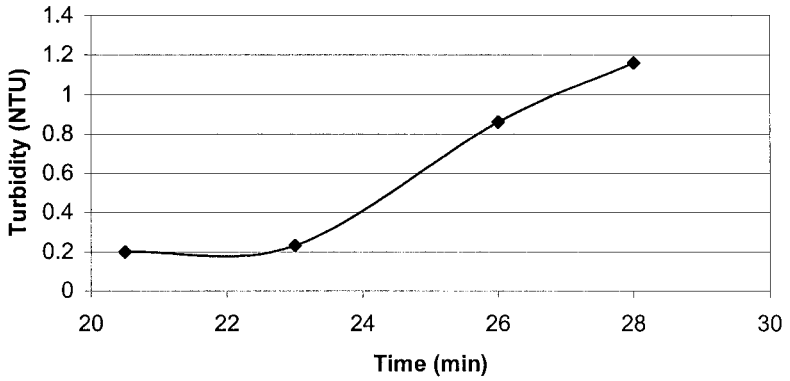

FIG. 4. Effect of turbidity on the time to achieve a 4-$\log_{10}$-U reduction in bacterial load for wastewater samples in the continuous solar disinfection unit. Water from four points in the Easton wastewater treatment facility (0.20 to 1.16 NTU) was treated in the solar disinfection unit. Each data point represents the average of three samples.

RESULTS

The pH, turbidity, and dissolved oxygen were measured before and after each experimental run (data not shown). There were insignificant differences between the properties of water entering and leaving the unit. The low turbidity values for the water samples (0.09 to 0.32 NTU) indicate that the water used in these experiments was relatively clear. Nitrate (<0.2 mg liter^{-1}) and orthophosphate (<0.2 mg liter^{-1}) were analyzed for one of the three samples tested in each run-time interval (22.5, 30, 45, and 60 min). The change in total bacterial counts over the span of residence times (from 7 to 74 min) for municipal wastewater samples is shown in Fig. 2. The temperature difference between the inflow and effluent of the unit ranged from 14 to 30.2°C, respectively.

Benchmark Analytics Laboratory confirmed our results of the municipal wastewater experiments with the solar disinfection unit (data not shown). Benchmark Analytics Laboratory tested the total coliform and noncoliform heterotrophic bacterial concentration in five samples: one from raw wastewater and four from experimental runs through the solar disinfection unit at residence times of 30 (two samples), 45, and 60 min. Except for the duplicate sample, all treated water samples contained <1 coliform/100 ml of water tested (6). The duplicate 30-min treatment sample contained 8 coliforms/100 ml of water.

Water from the Delaware River was used to test the effectiveness of the disinfection unit on treating water samples with a low level of bacterial contamination. Water was collected from the Delaware River 2 mi upstream from the Easton municipal drinking water treatment plant. The samples were tested in the solar disinfection unit at residence times of 9, 20.5, and 41 min (Fig. 3). In approximately 40 min, the coliform count was reduced by 2 orders of magnitude. Feed water entered the unit at 25°C; the temperature of the effluent was 35 and 45°C for the 9- and 41-min residence times, respectively.

Feed water samples with relatively increasing turbidities (NTU values between 0.20 and 1.16) were used to study the impact of turbidity on the rate of bacterial inactivation by the solar disinfection unit. Water samples were collected from the Easton wastewater treatment plant at four stages of purification: the inflow channel, off the weirs of the primary clarifier, influent to the secondary clarifier, and off the weirs of the secondary clarifier. These samples were filtered through cheesecloth to remove large particles that would have clogged the system without significantly affecting their turbidity. Wastewater samples were treated in the solar disinfection unit, and all samples had similar disinfection trends. The higher the turbidity of the sample, the longer the residence time required to reach a 4-$\log_{10}$-U reduction in bacterial load (Fig. 4).

A prototype of the solar disinfection unit was successfully tested by CEPIS in Lima by using controlled contaminated tap water samples. The average irradiation intensity ranged from 500 to 800 W m^{-2} with residence times of 20 to 60 min and final effluent temperatures of 50 to 60°C. The discrete values for radiation intensity reported in Table 1 are calculated based on the data collected under normal sun irradiation. Bacterial concentrations in the effluent were determined by membrane filtration with sulfate lauryl broth as the culture medium (17) followed by incubation at 44 ± 0.1°C for 24 h. With increasing residence time in the solar disinfection unit, an increase in temperature and a decrease in CFU of the mixed coliform culture occurred (Fig. 5). At an average flow rate of 0.4 ml/s the effluent temperature reached 55°C in approximately 44 min. During this process, the bacterial contamination was reduced by more than 4 $\log_{10}$ U (99.99%, Fig. 5).

DISCUSSION

We report the eradication of coliforms from highly contaminated water or wastewater by using a continuous flow solar

TABLE 1. Treatment time and flow rate to reach a 4-$\log_{10}$-U reduction of coliforms for the experiments conducted at CEPIS with controlled contaminated tap water

Final temp (°C)	Avg radiation (W m^{-2})							
	800		700		600		500	
	Time (min)	Flow (ml s^{-1})	Time (min)	Flow (ml s^{-1})	Time (min)	Flow (ml s^{-1})	Time (min)	Flow (ml s^{-1})
50	20	0.9	23	0.8	27	0.7	32	0.6
55	28	0.7	31	0.6	37	0.5	44	0.4
60	38	0.5	43	0.45	50	0.4	60	0.3

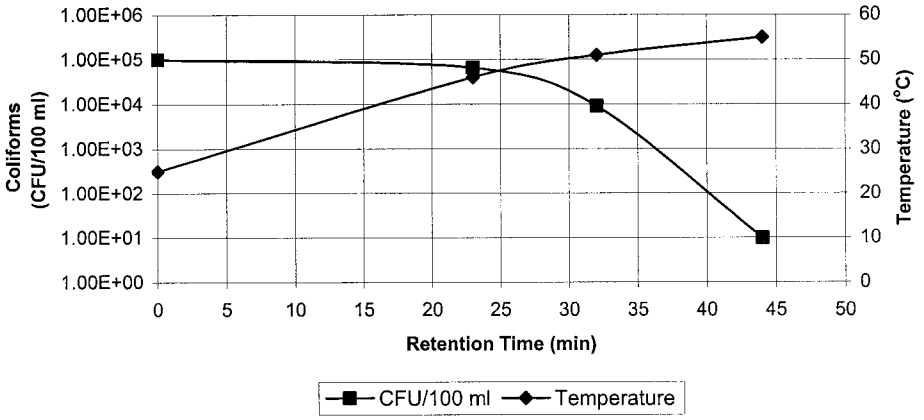

FIG. 5. Change in total coliform counts with increasing residence times in the continuous solar disinfection unit for a controlled contaminated water sample at CEPIS. Tap water samples were inoculated with 10^5 CFU of a culture of mixed coliforms/100 ml and processed in the solar disinfection unit at about 500 W of radiation/m^2 and an 0.4-ml/s flow rate. Each data point presents the average of three samples.

disinfection unit. The bacterial kill rate is highest during the first 30 min of the process (Fig. 2) and plateaus thereafter. By the use of this solar disinfection unit, decontamination below the level of detection (<1 coliform/100 ml) of partially treated wastewater occurs in 45 min, which is far faster than earlier reports (2, 14, 24). Our solar disinfection unit may be more efficient than other units because the exposure surface exceeds that of other tested units, thus maximizing the irradiation time. Joyce et al. (14) reported that complete disinfection of highly contaminated water (10^6 CFU/ml) in 2-liter transparent plastic bottles (a batch system) was achieved in 7 h by heating the water to approximately 55°C. No viable *E. coli* was observed over the following 12 h, indicating no bacterial recovery (14). A 3-log reduction in *E. coli* concentration by solar irradiation of contaminated water in a batch system in about 5 h has been reported (24). In a continuous flow reactor, 99.9% of total coliforms were eliminated in 90 to 310 min depending on the wavelength of light (320 to 490 nm, respectively [3]). The solar reactor tested in this study successfully eradicated more than 4 $\log_{10}$ U (99.99%) of total coliforms within 30 min in midday summer sunlight.

Water with low contamination (about 200 coliforms/100 ml) took longer to purify in the solar disinfection unit than did a more highly contaminated water sample (Fig. 2 and 3). This is in agreement with previous studies noting that less-contaminated water required a longer residence time for purification (23). Solar disinfection of water from the Kriesbach River (10 CFU/ml) required at least 500 W of solar radiation/m^2 for a period of 5 h (24).

The effect of turbidity on the bacterial inactivation is shown in Fig. 4. It is evident that turbidity inversely affected the kill rate for bacteria; at higher turbidities, a longer time was needed to obtain the 4-$\log_{10}$-U reduction of coliforms. This finding corroborates similar results that have shown enhanced bacterial elimination under similar light intensity by lowering turbidity (2, 14, 24).

Experiments with controlled water samples at CEPIS demonstrated the interaction of radiation intensity, flow rate, and reaction space-time to achieve a similar coliform level (Table 1). At 800 W/m^2, 60°C, and 0.5 ml/s, it took 32 min to reach 10 coliforms/100 ml whereas it took 60 min to reach similar results at 500 W/m^2, 60°C, and 0.3 ml/s. These experiments point to the effectiveness of the solar unit in eradicating contaminating bacteria under a variety of radiation intensities and flow rates.

In summary, a solar disinfection unit has been designed and successfully tested for disinfection of contaminated water under polychromatic solar light. The unit destroyed more than 99% of bacterial coliforms in both controlled and naturally contaminated water samples in less than 30 min. The unit is portable, and it can easily produce 2 gal of treated water on a sunny summer day. The major application of solar water disinfection could come in areas rich in sunshine but distant from reliable water purification systems.

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